A&A manuscript no.
(will be inserted by hand later)

Your thesaurus codes are:
1(08.05.1; 08.19.2; 08.16.3; 10.07.3 M 15)

ASTRONOMY
AND
ASTROPHYSICS
1.2.2008

Hot HB stars in globular clusters - physical parameters and consequences for theory

IV. sdB candidates in M 15

S. Moehler[1,2] ⋆, U. Heber[3], and P.R. Durrell[4]

[1] Landessternwarte, Königstuhl, 69117 Heidelberg, Federal Republic of Germany
[2] Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA (e-mail: smoehler@stsci.edu)
[3] Dr. Remeis-Sternwarte, Sternwartstr. 7, D 96049 Bamberg, Germany
[4] Dept. of Physics & Astronomy, McMaster University, Hamilton, ON, Canada, L8S 4M1

February 1, 2008

Abstract. Quantitative spectroscopic analyses of two faint blue stars (V=$19^{\rm m}_{\cdot}5$ – $20^{\rm m}_{\cdot}0$) in the globular cluster M 15 are presented. Their derived $T_{\rm eff}$, gravities and absolute magnitudes ($T_{\rm eff}$=24000K, log g=5.2, $M_V=4^{\rm m}_{\cdot}3$; $T_{\rm eff}$=36000K, log g=5.9, $M_V=4^{\rm m}_{\cdot}7$, respectively) are matched very well by models for the Extreme Horizontal Branch (EHB). Both stars are bona-fide subdwarf B stars making M 15 only the second globular cluster (after NGC 6752) for which the existence of sdB stars has been proven spectroscopically. While the helium abundance (one tenth solar) of F1-1 is typical for sdB stars, F2-2 surprisingly turned out to be a helium rich star, the first to be reported as a member of a globular cluster. In the field population of the Milky Way such stars are rare (less than 5% of all sdB stars). From its proximity to the helium main sequence, it is speculated that F2-2 may be a naked helium core, i.e. an Extreme Horizontal Branch star which lost (almost) all of its hydrogen-rich envelope.

Key words: Stars: early-type – Stars: subdwarfs – Stars: Population II – globular clusters: M 15

1. Introduction

Subluminous B stars (sdB) form the extreme blue end ($T_{\rm eff} > 20000$ K and log g > 5) of the Horizontal Branch (Heber et al., 1984) and are therefore termed Extreme Horizontal Branch (EHB) stars. Such objects are now believed to be the dominant source of UV radiation causing the UV upturn phenomenon in elliptical galaxies and galaxy bulges (Dorman et al., 1995). While there are more than a thousand sdBs known in the field of our galaxy (Kilkenny et al., 1988), only in one globular cluster bona-fide sdB stars were shown to exist (NGC 6752, Heber et al., 1986, Moehler et al., 1996). Several claims that sdB stars had been found in other globular clusters too could not be confirmed by spectroscopic analyses. Moehler et al. (1995, 1996, de Boer et al. 1995, hereafter Paper I,III, and II respectively) found that all "classical" BHB stars (i.e. stars with $T_{\rm eff} < 20000$ K and log g < 5) in several clusters exhibited too low masses compared to standard evolutionary theory, whereas the sdB stars' masses in NGC 6752 were in good agreement with the canonical mass of 0.5 $M_\odot$.

It is therefore of great importance to find and analyse sdB stars in other globular clusters. In this letter we present follow-up spectroscopy and spectral analyses of faint blue stars ($19^{\rm m} <$ V $< 20^{\rm m}$ and $-0^{\rm m}_{\cdot}28 <$ (B−V) $< -0^{\rm m}_{\cdot}12$) in the globular cluster M 15, which were discovered recently by Durrell & Harris (1993).

2. Observations and Reduction

Two of the four candidates (F2-1 and F2-3) could not be observed reliably from the ground due to nearby red neighbours (see Table 1). The remaining candidate stars were observed with the focal reducer of the 3.5m telescope at the Calar Alto observatory using grism #3 (134 Å/mm) and a slit width of 1''.5, resulting in medium resolution spectra covering the wavelength range 3250 - 6350 Å. We also obtained low resolution spectrophotometric data, us-

Send offprint requests to: U. Heber

⋆ Visiting Astronomer, German-Spanish Astronomical Center, Calar Alto, operated by the Max-Planck-Institut für Astronomie jointly with the Spanish National Commission for Astronomy

ing a slit width of 5″ and binning the spectra by a factor of 2 along the dispersion axis.

Number	V	B−V	α_{2000}	δ_{2000}
F1-1	19ᵐ.468	−0ᵐ.160	21ʰ30ᵐ12ˢ.3	+12°03′45″.6
F2-1	19ᵐ.101	−0ᵐ.126	21ʰ29ᵐ39ˢ.6	+12°07′26″.3
	18ᵐ.555	+1ᵐ.531	21ʰ29ᵐ39ˢ.6	+12°07′26″.8
F2-2	19ᵐ.983	−0ᵐ.231	21ʰ29ᵐ34ˢ.7	+12°09′19″.1
F2-3	19ᵐ.956	−0ᵐ.276	21ʰ29ᵐ46ˢ.6	+12°06′53″.7
	18ᵐ.027	+0ᵐ.702	21ʰ29ᵐ46ˢ.6	+12°06′54″.3

Table 1. Positions and magnitudes of the sdB candidates and their close neighbours

Since there is no built-in wavelength calibration lamp we observed wavelength calibration spectra only at the beginning of the night. The observation and calibration of bias, dark current and flat-field was performed as described in paper I and III. As the focal reducer produces rather strong distortions we extracted that part of each observation that contained the desired spectrum and some sky and straightened it, using a program written by Dr. O. Stahl (priv. comm.). We applied the same procedure to the wavelength calibration frames. Thereby we could perform a good two-dimensional wavelength calibration (using the MIDAS Long context) and sky-subtraction (as described in paper I). Correction of atmospheric and interstellar extinction as well as flux calibration was again performed as described in paper I using the flux tables of Massey (1988) for BD+28°4211.

3. Analyses

3.1. F1-1

The spectra show broad Balmer lines and a weak He I line at 4471 Å typical for sdB stars. The low resolution data unfortunately showed some excess flux towards the red, probably caused by a red star (V = 19ᵐ.99, B−V = +0ᵐ.55) 3″ away. Fitting only the Balmer jump and the B and V photometry of Durrell & Harris (1993) we get an effective temperature of 24000 K (cf. paper III). We used the helium- and metal-poor model atmospheres of Heber (cf. Paper III) to analyse the medium resolution spectrum of F1-1. As the resolution of the spectrum varies with wavelength we convolved the model atmospheres with different Gaussian profiles for the three Balmer lines. The appropriate FWHM were determined from the calibration lines close to the position of the Balmer lines. We used FWHM of 8.7 Å for H_δ, 7.1 Å for H_γ, and 9.8 Å for H_β. We fitted each line separately and derived the mean surface gravity by calculating the weighted mean of the individual results. The weights were derived from the fit residuals of the individual lines. We thus get a log g value of 5.2±0.14 for a fixed effective temperature of 24000 K. The fits to the Balmer lines are shown in Fig. 1. Note in passing that higher temperature and gravity results if we ignore the Balmer jump and derive $T_{\rm eff}$ and log g simultaneously from the three Balmer line profiles alone: The smallest overall residual is achieved for $T_{\rm eff}$ = 29700 K and log g = 5.9. These values, however, are inconsistent with the low resolution data. We already noted similar inconsistencies between Balmer jump and Balmer line profiles in paper I, which are probably caused by insufficient S/N in the Balmer line profiles. The He I 4471 Å line is consistent with a helium abundance of about 0.1 solar. Using the routines of R. Saffer (Saffer et al., 1994) and a fixed mean FWHM of 8 Å we get internal errors of 600 K and 0.13 dex, respectively. We take the standard deviation of log g as external errors and assume an external error of $T_{\rm eff}$ of ± 2000 K (cf. Paper III). Using the same method as in Papers I and III we get a logarithmic mass of −0.423±0.20 dex, corresponding to $(0.38^{+0.22}_{-0.14})$ $M_\odot$. For a detailed discussion of the errors entering into the mass determination see Paper III.

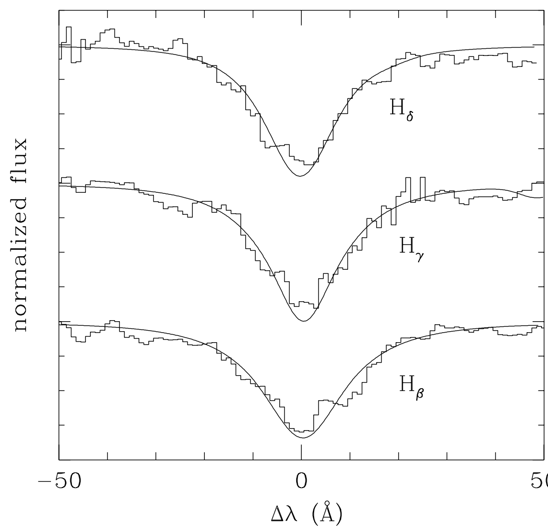

Fig. 1. The best fitting models for $T_{\rm eff}$ = 24000 K compared to the Balmer lines of of F1-1 (log g = 5.0 (H_δ), 5.3 (H_γ, H_β)). The tickmarks mark steps of 10% in intensity.

3.2. F2-2

Unlike F1-1 and other sdBs the spectrum of F2-2 is not dominated by Balmer lines but displays a prominent He I absorption line spectrum in addition to the Balmer lines (see Fig.2). The Balmer lines are much weaker and narrower than in F1-1. In Fig. 2 we compare the spectrum of F2-2 (smoothed by a box filter of 5 Å width) to that of a He-sdB in the field (HS 0315+3355, Heber et al. 1996), a spectral type that describes rare helium-rich variants of the sdB stars (Moehler et al., 1990, see also below), The helium line spectra of both stars are very similar, while the Balmer lines in HS 0315+3355 are considerably

weaker than in F2-2 (see Fig. 2), indicating an even lower hydrogen content of the former.

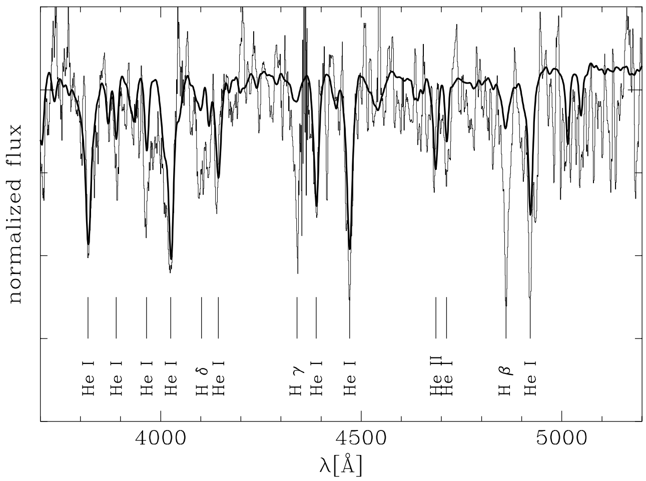

Fig. 2. The medium resolved spectrum of F2-2 and the identified absorption lines. To allow a better identification of the lines the spectrum has been smoothed with a box filter of 5Å width. In comparison (thick line) we show the spectrum of a helium-rich sdB star (HS 0315+3355) in the field that has been convolved to the same resolution. The tickmarks mark steps of 10% in intensity.

The admittedly rather low S/N unfortunately allows only a coarse analysis. Since an analysis of individual spectral lines is impossible we choose to fit the entire useful portion of the spectrum (4000Å – 5000Å) simultaneously. It turned out that F2-2 is somewhat hotter than F1-1 and we therefore used the updated grid of NLTE model atmospheres calculated by S. Dreizler (see Dreizler et al. 1990). The model atmospheres include detailed H and He model atoms and the blanketing effects of their spectral lines but no metals. Using Saffer's fitting program $T_{\rm eff}$, log g, and helium abundance were determined simultaneously from a small subgrid ($T_{\rm eff}$ = 35, 40, 45kK; log g = 5.5, 6.0, 6.5; He/(H+He) = 0.5, 0.75, 0.91, 0.99, by number).

Since the He I 4144Å line is not included in the models, this line is excluded from the fit.

An effective temperature of 36000 K, log g of 5.9, and a helium abundance of $N_{He}/(N_H+N_{He}) = 0.87$ (by number) resulted. The fit to the spectrum is displayed in Fig. 3. Since the noise level is rather high it is difficult to estimate the error ranges of the atmospheric parameters. As a test we changed the fitted spectral range as well as the placement of the continuum, which resulted in quite small changes of $T_{\rm eff}$ (≈ 2000K) and log g (≈ 0.2 dex). The helium abundance $N_{He}/(N_H+N_{He})$ ranged from 0.5 to 0.9 by number, indicating that helium is overabundant by at least a factor 5 with respect to the sun. As conservative error estimates we adopted ± 4000 K and 0.5 dex for the errors in $T_{\rm eff}$ and log g.

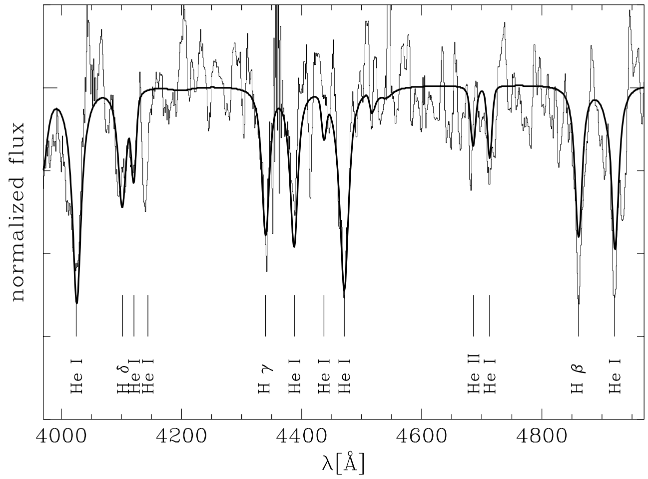

Fig. 3. The spectrum of F2-2 and the best fitting model (thick line, $T_{\rm eff}$ = 36000 K, log g = 5.9, $N_{He}/(N_H+N_{He}) = 0.87$). To allow a better identification of the lines the observed spectrum has been smoothed with a box filter of 5Å width. The tickmarks mark steps of 10% in intensity.

3.3. Radial velocities

For F1-1 we derive a mean heliocentric velocity of −142 km/sec from the Balmer lines with an estimated error of about ±40 km/sec (due to the mediocre resolution, the limited accuracy of the wavelength calibration, and the shallow lines). This value is within the error limits consistent with the cluster velocity of -107.09 km/sec (Peterson et al., 1989). For F2-2 we could not derive reliable radial velocities from single lines due to the low S/N of the spectrum. Instead we cross correlated the normalized spectrum with that of the field He-sdB HS 0315+3355 (convolved to the same resolution). This procedure resulted in a heliocentric velocity of ≈ −70 km/sec, which - due to the large errors - does not contradict a cluster membership for F2-2.

4. Discussion

The spectroscopic analyses of two faint blue stars in the globular cluster M 15 show that both stars are bona-fide subdwarf B stars. In Fig. 4 and 5 we compare their positions in the ($T_{\rm eff}$, log g)- and the ($T_{\rm eff}$, M_V)-diagrams to those of EHB stars in NGC 6752 (from paper III) as well as to the predictions from Horizontal Branch stellar models (from Dorman et al. 1993). As can be seen from this comparison, their evolutionary status is well described by models for the Extreme Horizontal Branch (EHB). Hence M 15 is only the second globular cluster (after NGC 6752) for which the existence of EHB stars has been proven spectroscopically. While the helium abundance of F1-1 is typical for sdB stars (i.e. subsolar), F2-2 surprisingly turned out to be a helium rich star.

This is the first time ever that a helium rich sdB star has been reported in a globular cluster. In the field of the Milky Way only 5% of the sdB stars are helium-rich. Jeffery et al. (1996) list 48 such stars, while the latest (unpub-

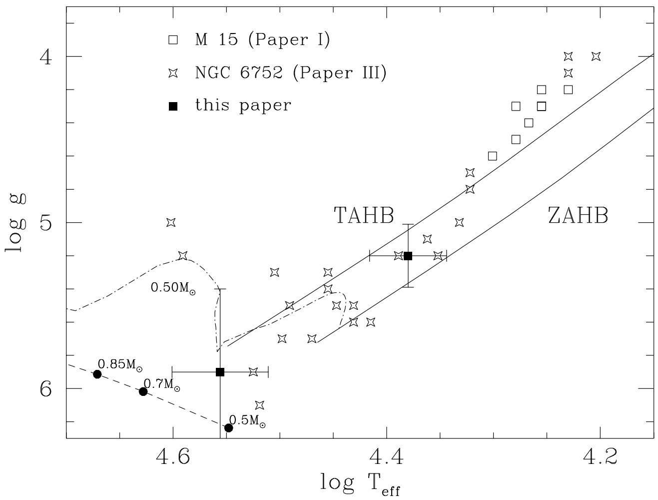

Fig. 4. The physical parameters of the sdBs in M15 compared to the results of Papers I and III and to theoretical expectations. The solid lines are the Zero Age HB and the Terminal Age (core helium exhaustion) HB for [Fe/H] = −2.26 of Dorman et al. (1993). The short dashed line gives the position of the helium main sequence (Paczynski 1971). The long dashed-short dashed lines give post-EHB evolutionary tracks by Dorman et al. (1993), labeled with the total mass of the EHB star.

lished) version of the catalog of hot subdwarfs (Kilkenny et al., 1988) lists more than 1,000 hydrogen-rich sdBs.

The helium-rich sdB has an absolute visual brightness of about $4\overset{m}{.}7$, which places it at the very faint blue end of the EHB as seen in the colour-magnitude diagram of NGC 6752. F2-2 may even be hotter than any EHB star in NGC 6752. From its proximity to the helium main sequence in Fig. 4 and 5 it might be tempting to regard F2-2 as a naked helium core, i.e. as an Extreme Horizontal Branch star which lost (almost) all of its hydrogen-rich envelope.

Why didn't we find any helium-rich sdBs in NGC 6752? All the EHB stars that have been analysed in NGC 6752 (including the three faintest ones seen in Buonanno et al., 1986) are helium-poor sdB stars (Paper III). This could either mean that there are no helium-rich subdwarfs in NGC 6752 or that they are just below the detection limit of Buonanno et al. (1986). One should certainly keep an eye on newer and deeper CMDs of globular clusters to see whether other He-sdB candidates show up.

Acknowledgements. We thank Dr. S. Dreizler for making available his NLTE model grid to us and the staff of the Calar Alto Observatory for their support during the observations. Thanks go also to Dr. R. Saffer for valuable discussions. SM acknowledges support from the DFG (Mo 602/5-1), by the Alexander von Humboldt-Foundation, and by the director of STScI, Dr. R. Williams, through a DDRF grant.

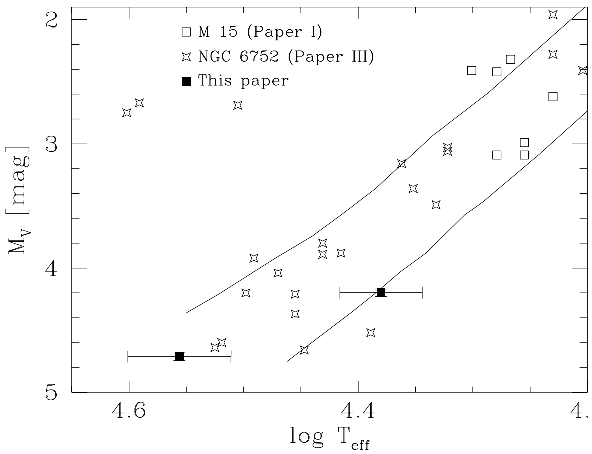

Fig. 5. The absolute V magnitudes and effective temperatures as given above compared to theoretical tracks by Dorman et al. (1993, details see Fig. 4). Also shown are the data for the stars analysed in papers I and III.

References

de Boer K.S., Schmidt J.H.K., Heber U., 1995, A&A 303, 95 (paper II)

Buonanno R., Caloi V., Castellani V., Corsi C.E., Fusi Pecci F., Gratton R., 1986, A&AS 66, 79

Dorman B., Rood R.T., O'Connell, R.W., 1993, ApJ 419, 596

Dorman B., O'Connell R.W., Rood R.T., 1995, ApJ 442, 105

Dreizler, Heber U., Werner K., Moehler S., de Boer K.S. 1990, A&A 235, 234

Durrell P.R., Harris W.E., 1993, AJ 105, 1420

Heber U., Hunger K., Jonas G., Kudritzki R.P., R.P., 1984, A&A 130, 119

Heber U., Kudritzki R.P., Caloi V., Castellani V., Danziger J., Gilmozzi, 1986, A&A 162, 171

Heber U., Dreizler S., Werner K., Engels D., Hagen H.-J., 1996, ASPC 96, 241

Jeffery C.S., Heber U., Hill P.W., Dreizler S., Drilling J.S., Lawson, W.A., Leuenhagen U., Werner K., 1996, ASPC 96, 471

Kilkenny D., Heber U., Drilling J.S., 1988, SAAOC 12, 1

Massey P., Strobel K., Barnes J.V., Anderson E., 1988, ApJ 328, 315

Moehler S., Richtler T., de Boer K.S., Dettmar R.J., Heber U., 1990, A&AS 86, 53

Moehler S., Heber U., de Boer K.S., 1995, A&A 294, 65 (paper I)

Moehler S., Heber U., Rupprecht G., 1996, A&A in press (paper III)

Paczynski B., 1971, Acta Astron. 21, 1

Peterson R.C., Seitzer P., Cudworth K.M., 1989, ApJ 347, 251

Saffer R.A., Bergeron P., Koester D., Liebert J., 1994, ApJ 432, 351

This article was processed by the author using Springer-Verlag LaTeX A&A style file *L-AA* version 3.